Structural Behavior and Stability Under Fire Loading

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Motivation

- This research project is inspired by the findings of the 9/11 WTC collapse investigations conducted by NIST BFRL researchers.
- The WTC collapse investigations led to the development of several major recommendations for future research.
  - R9.1 – Develop and validate analytical tools, guidelines, and test methods necessary to evaluate the fire performance of the structure as a whole system.
  - R9.2 – Develop performance-based standards and code provisions to enable the design and retrofit of structures to resist real building fire conditions.
- The research project will make fundamental contributions and progress towards achieving R9.1 and R9.2 noted above
  - The focus is on R9.1 - development of analytical tools, approaches and experimental methods

RESEARCH MOTIVATION AND GOAL

- The research project is motivated by the need for:
  - (a) fundamental knowledge of structural behavior and stability failure under fire loading, and
  - (b) numerical tools that can be used efficiently to calculate structural response and capacity under fire loading.
- The overall goal of this research project is to develop and experimentally validate numerical models and approaches that can be used to compute structural response and the potential for stability failure under realistic fire loading.
- The models must include different levels of complexity
  - Simple and quick analysis models for decision making during extreme fire events.
  - Detailed models for performance evaluation and retrofit design of existing buildings, and design of future buildings
  - Complex models for forensic analysis after an extreme event, or planning for protecting important structures.

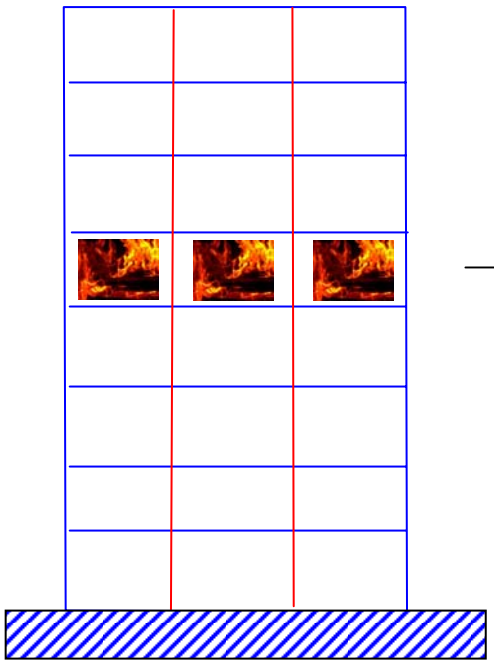
RESEARCH OBJECTIVES

- The objectives of the research project are:
  - To develop and experimentally validate numerical models for predicting the structural behavior and collapse (inelastic stability failure) of steel columns subjected to realistic (non-standard) fire loading conditions.
  - To develop and experimentally validate numerical models for predicting the structural behavior and collapse of steel column sub-systems and complete stories subjected to realistic fire loading conditions.
  - To evaluate the effects of various parameters (structural configuration, loading, and fire protection) on the structural behavior and stability failure of steel structures under realistic fire loading conditions.
  - To develop software tools and numerical approaches implementing models with different levels of complexity for evaluating structural behavior and stability failure under fire loading.

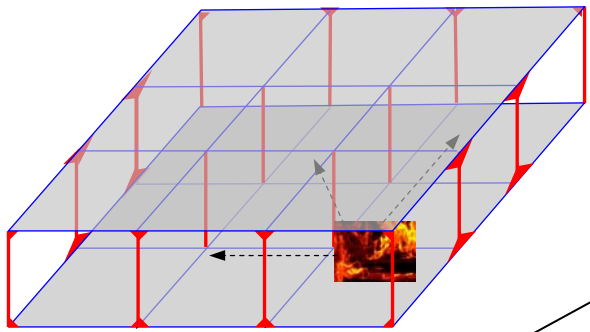
Research Vision and Approach

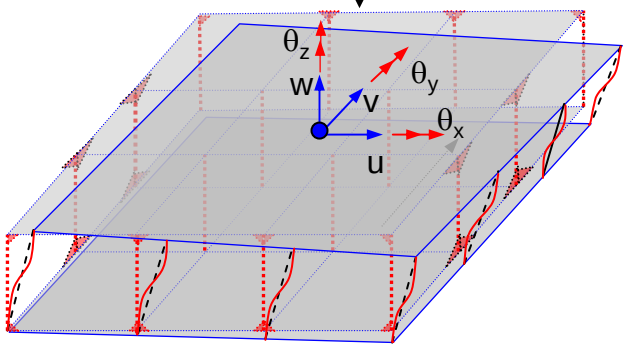
- The focus of this research is on story stability or collapse under realistic fire loading conditions.

Building structure under compartment fire loading

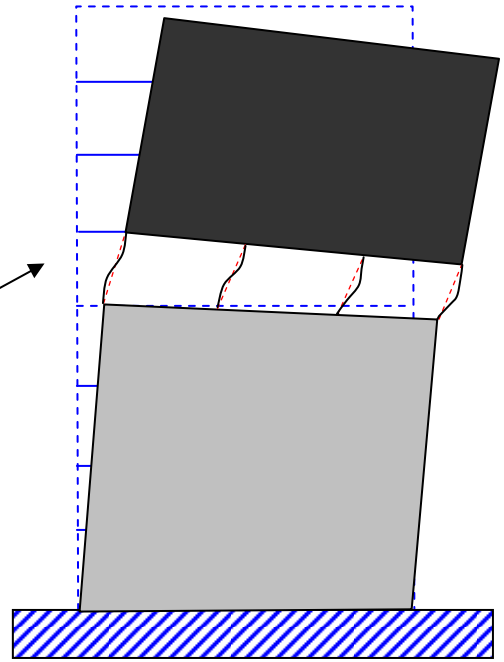


Structural configuration of story with fire spreading to compartments





Story stability failure or collapse mechanism - hypothesis

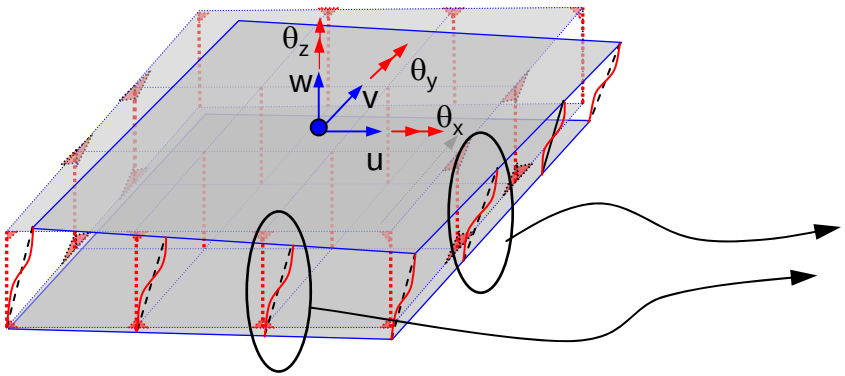


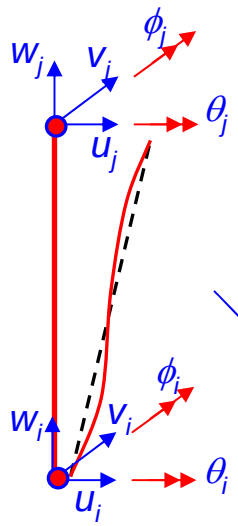
Structural failure or collapse initiation - hypothesis

Research Vision and Approach

- Material behavior - existing literature databases
  - Thermal properties (k, c_p) vs. temperature, thermal expansions (α) vs. temperature, stress-strain (σ–ε) vs. temperature
- Section behavior - fiber models integrating material behavior
  - Fundamental (P-M_x-M_y) vs. (ε_c-ϕ_x-ϕ_y) responses as functions of temperature (T) distributions through the cross-section.
- Member behavior - section fiber models integrated over member length
  - Axial force (P) - displacement (u, *v, w …*) behaviors for different temperature distributions and end conditions including axial and rotational restraints
- Story behavior and stability - member behavior integrated for structural configuration using hypothesis for story deformation and compatibility and force equilibrium
  - Story axial load (ΣP) - displacement (u, v, w …) behavior for temperature distributions and fire evolution through the story.
  - Story axial load capacity (ΣP_n) as function of time corresponding to fire spread evolution through the story

Research Vision and Approach

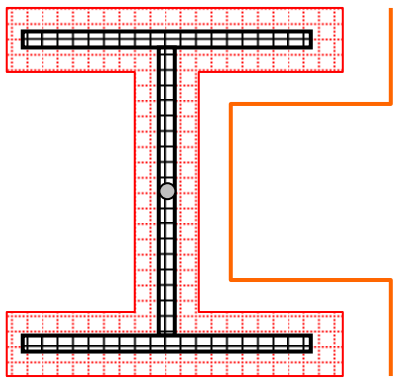




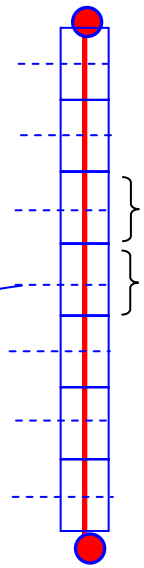
Structural member subjected to:
(a) Forces due to loads
(b) Deformations due to story stability
(c) Elevated temperatures due to fire loading and evolution

Fire protection thickness
Fiber temperatures T_{fib}

Generalized strains ε_c, ϕ_x, ϕ_y
Generalized stresses P, M_x, M_y



Heating of one or more sides



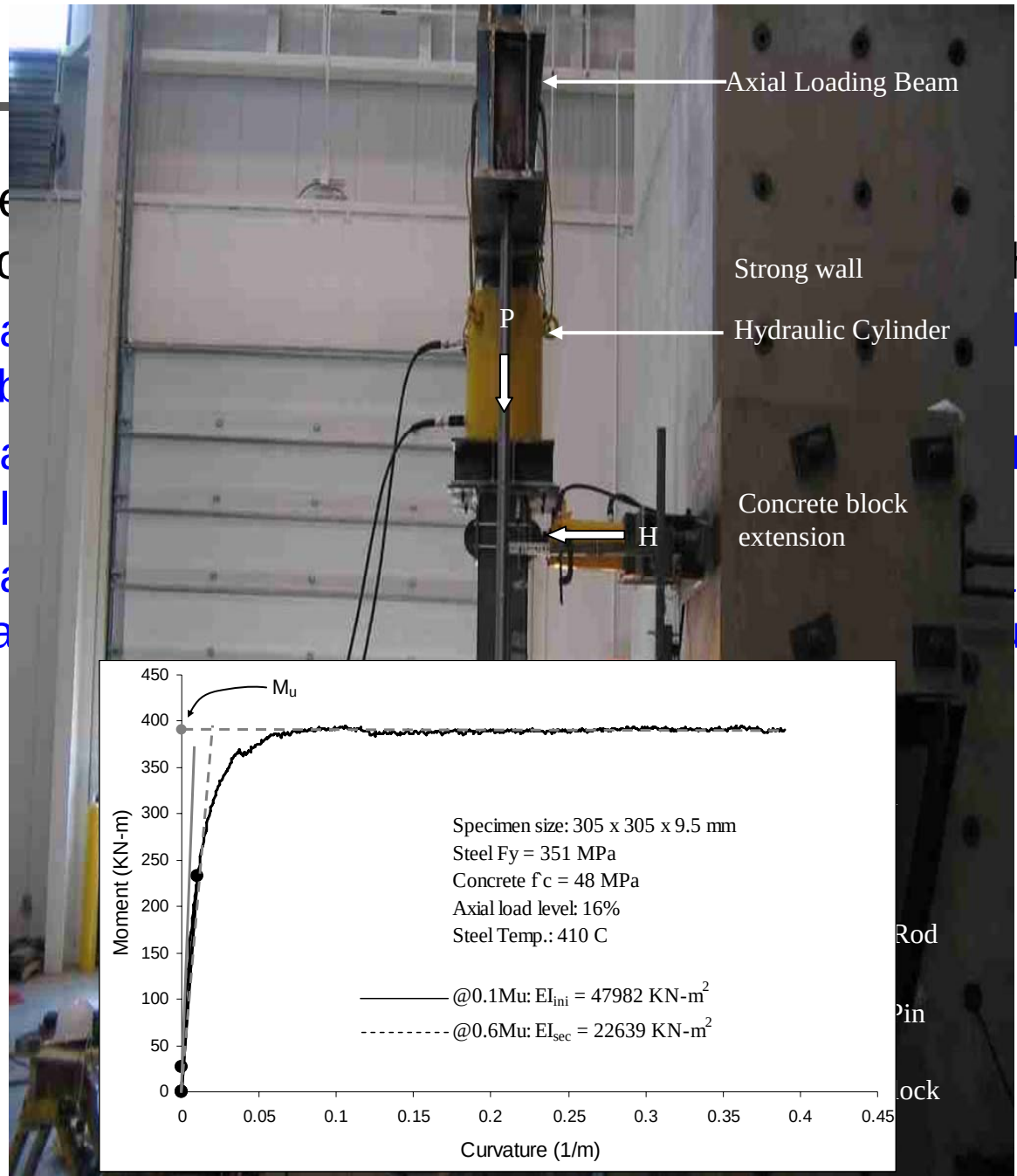
Section fiber model at the middle of each segment

Member length divided into segments

Current Progress - 1

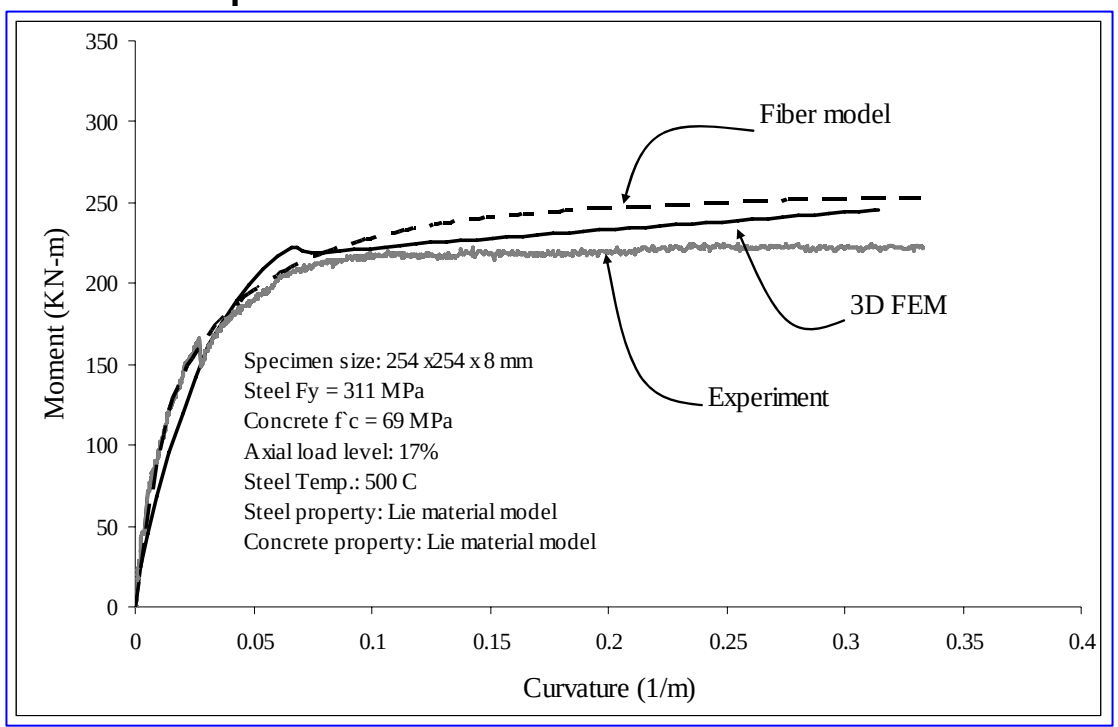
- Developed numerical models and approaches for calculating:
  - Fundamental section behavior using fiber models and material properties from literature databases
  - Member (column) behavior subjected to combined axial load and elevated temperatures from fire loading
- Validated the numerical models and approaches
  - Experimentally by testing composite CFT columns to measure the fundamental section P-M-ϕ-T behavior at elevated temperatures from standard fire loading.
  - Analytically by predicting and comparing the standard fire behavior and failure of composite CFT column specimens tested by researchers from around the world.
- Extended the validated model to predict the fundamental section and overall member (column) behavior of
  - Steel columns with arbitrary cross-section and non-uniform temperature distributions from non-standard or realistic fire loading.
  - These predictions need to be validated experimentally in the near future.

- Experime ial force-strain-mo havior
  - Specia bined axial load, b
  - Specia heaters and el
  - Specia l behavior (avera ures)



Fundamental Section Behavior

- Experimental results were compared with computations using 3D finite element models of the specimens. These comparisons validated the measurements and the models.
- The experimental results were used to develop and calibrate the fiber model for predicting the fundamental section behavior at elevated temperature distributions



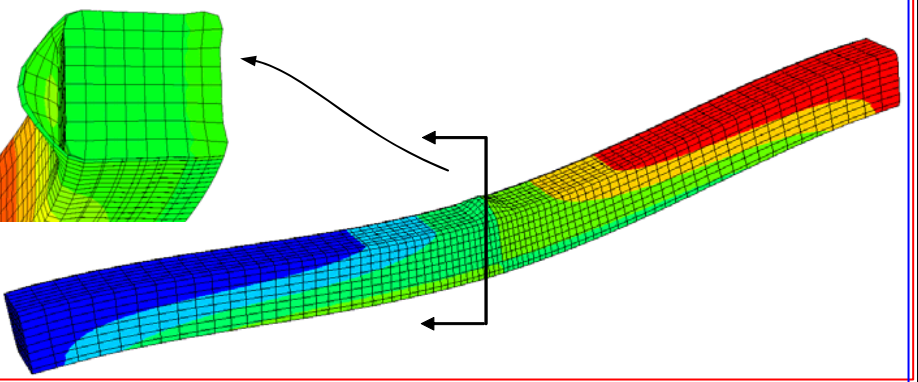
Member Behavior Model

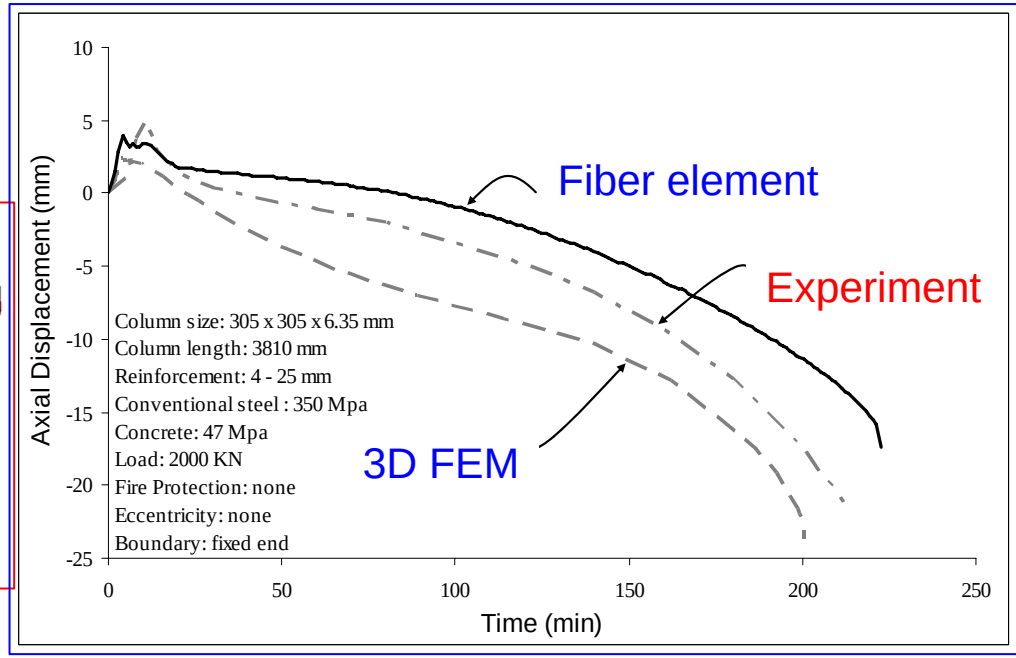
- The validated section fiber models were used to develop a fiber element for predicting column inelastic stability and failure under fire loading.
  - The element was used to predict the standard fire behavior of CFT column specimens tested by other researchers.
  - The element was validated by comparing predictions with experimental results and the results from 3D finite element models

Member Behavior Model

- 3D finite element models were also developed to predict the standard fire behavior of composite CFT columns.

3D finite element model





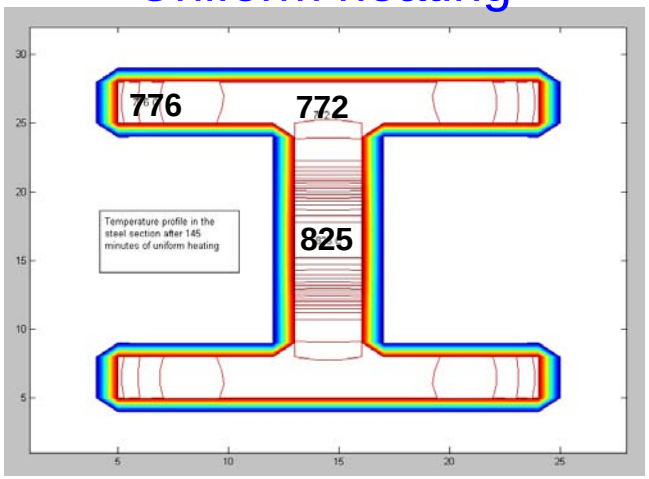
- The fiber element offers a much simpler way to predict behavior and stability failure as compared to 3D finite element models.

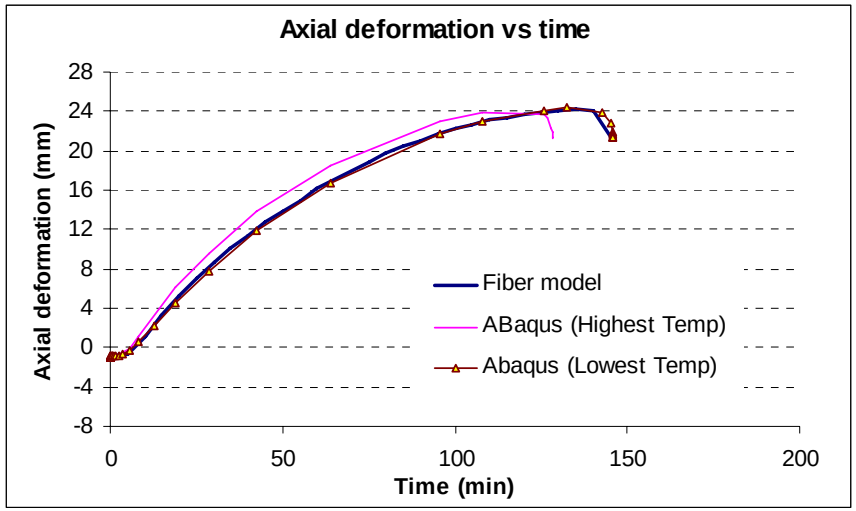
Member Behavior Model

- The validated fiber element is being modified and extended for steel columns of general configuration and heating (uniform or non-uniform).
  - Any cross-section made up of several materials and with fire protection
  - Heating applied on one or several sides of the section.
  - Axial load so far …
- The model can be used to compute the axial force-displacement-temperature *(P-u-T)* behavior and inelastic failure capacity (P_n-t) as function of time or temperature of heating
  - The predictions have been compared with those made using a beam-column finite element with material inelasticity, section behavior, and temperature degree of freedom
  - The predictions compare reasonably well with those using the beam-column finite element model.
  - Additional comparisons and numerical validations are ongoing

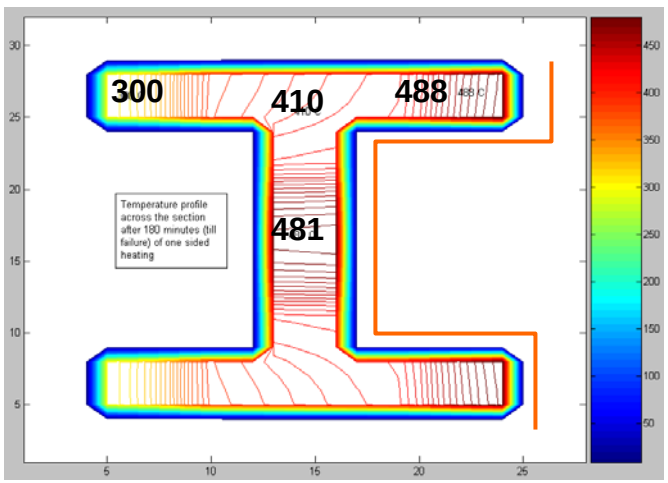
General Column Model

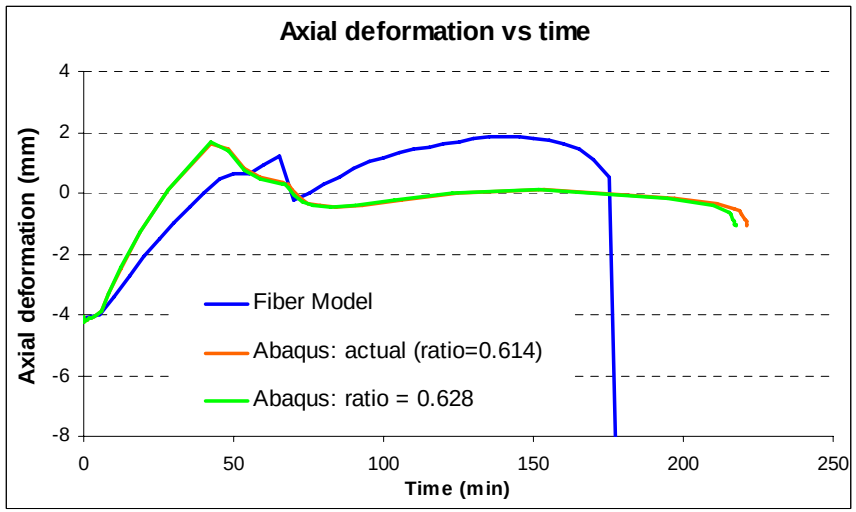
Uniform heating





Non-uniform one-sided heating



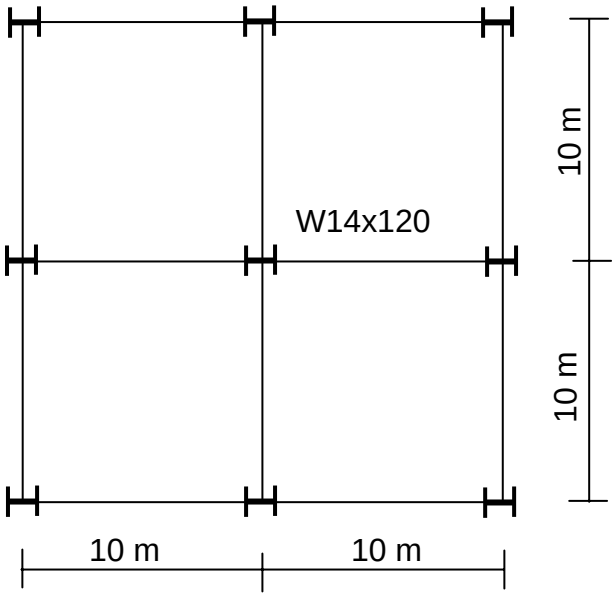


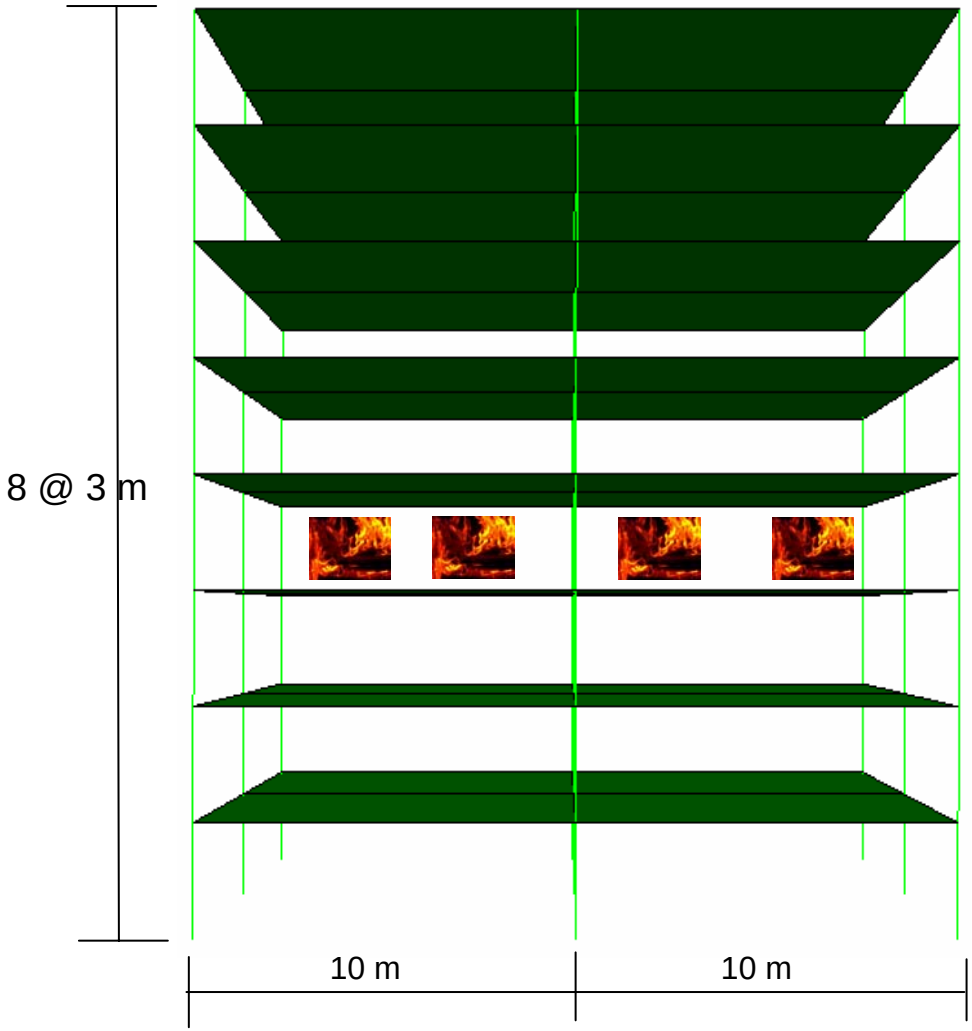
Current Progress -2

- Developing numerical models for simulating the story stability behavior of steel structures under realistic fire loading. Two approaches are being used.
  - (1) 3D Finite element models of the structure and story under consideration
    - The columns are modeled using beam-column finite elements with temperature-dependent inelasticity
    - The floors are modeled using plate elements
    - The story and structure behavior are established using nonlinear finite element analysis .
  - (2) Story behavior estimated by integrating member (column) responses.
    - The story behavior and stability is established by enforcing force equilibrium and displacement compatibility between the columns of the story at time steps and temperature distributions.
    - The column (axial force vs. displacements) behaviors for different temperature distributions are computed using fiber element models.

Story Stability Investigations (1)

EXAMPLE

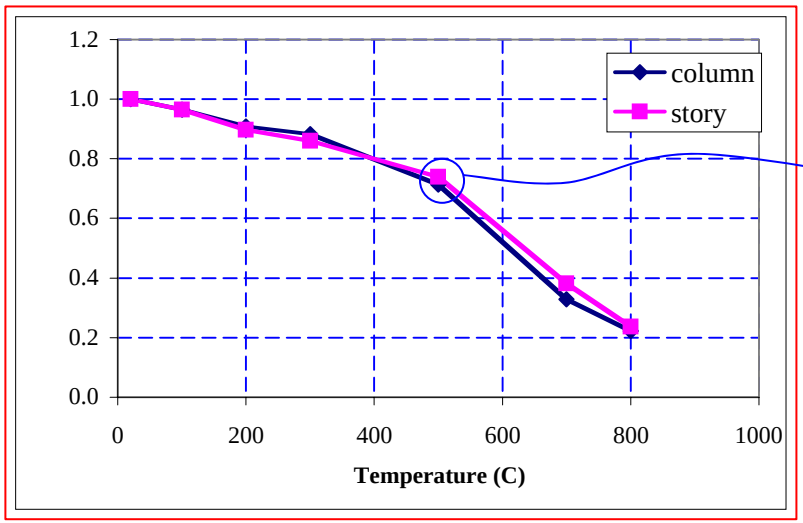




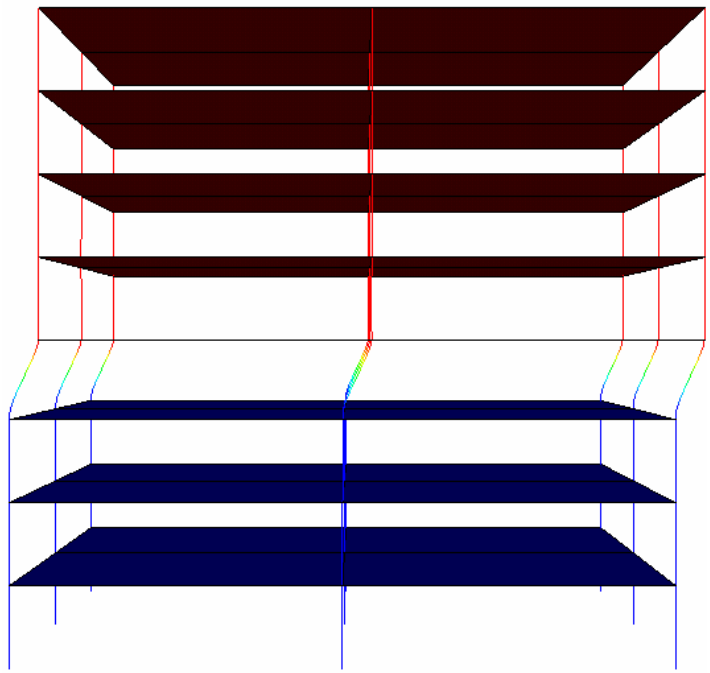
- Columns (B33), Slab (S4R)
- Riks analysis using ABAQUS
- *Uniform temperatures* were applied on the columns

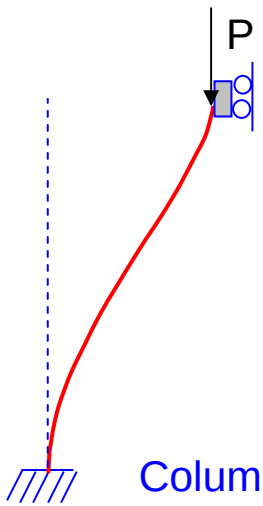
Story Stability Investigations

Story capacity with respect to column temperatures



Typical story failure mode at uniform temperatures

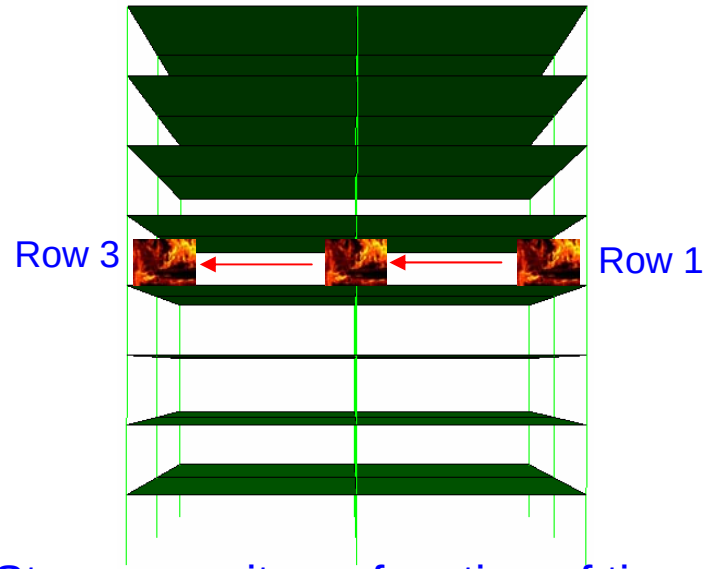




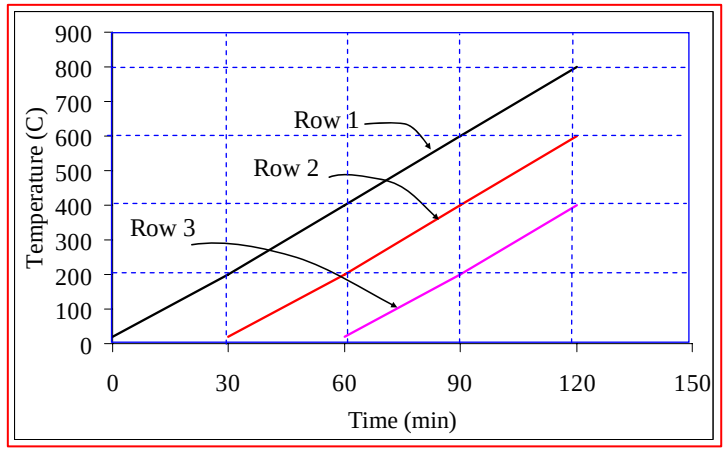
Column buckling failure mode

Story Stability Investigations

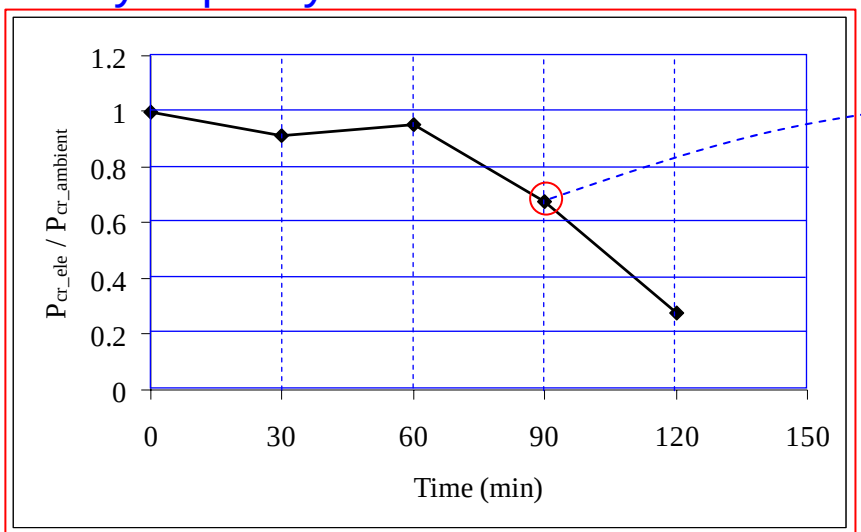
Compartment fire spreading



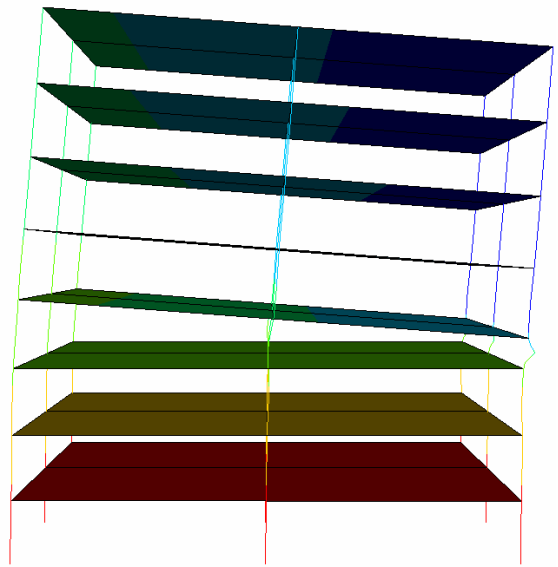
Column T-t curves



Story capacity as function of time

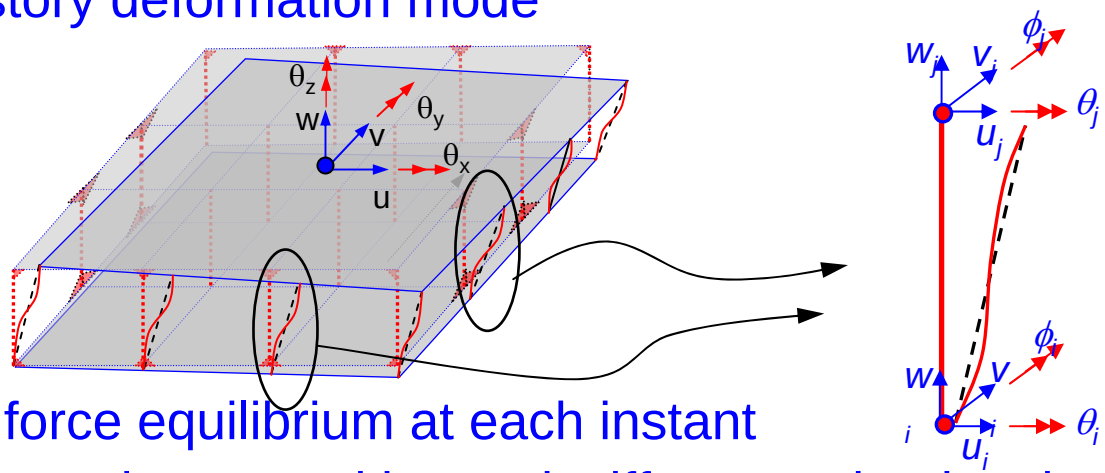


Failure mode at 90 min.



Story Stability Modeling (2)

- Using fiber element and deformation hypothesis for story stability based on results of 3D finite element models
  - At each time instant, estimate temperature distributions for the members
  - Establish member capacities and stiffness at the time instant using the fiber element and temperature distributions
  - Assume story deformation mode



  - Establish force equilibrium at each instant using the member capacities and stiffness at the time instant.
- Development in progress. Experimental and numerical validation to be designed.

Acknowledgments

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- NSF (Dr. Douglas Foutch - cognizant program official)
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